Renewable and Sustainable Energy Reviews 16 (2012) 274–283

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Overview of energy storage systems for storing electricity from renewable energy sources in Saudi Arabia

Faizur Rahman*, Shafiqur Rehman, Mohammed Arif Abdul-Majeed

Center of Research Excellence in Renewable Energy, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia

ARTICLE INFO

Article history:
Received 22 May 2011
Accepted 7 July 2011
Available online 23 September 2011

Keywords:
Electrical energy storage
Renewable energy
Energy management
Solar
Wind
Storage battery

ABSTRACT

Renewable power (photovoltaic, solar thermal or wind) is inherently intermittent and fluctuating. If renewable power has to become a major source of base-load dispatchable power, electricity storage systems of multi-MW capacity and multi-hours duration are indispensable. An overview of the advanced energy storage systems to store electrical energy generated by renewable energy sources is presented along with climatic conditions and supply demand situation of power in Saudi Arabia. Based on the review, battery features needed for the storage of electricity generated from renewable energy sources are: low cost, high efficiency, long cycle life, mature technology, withstand high ambient temperatures, large power and energy capacities and environmentally benign. Although there are various commercially available electrical energy storage systems (EESS), no single storage system meets all the requirements for an ideal EESS. Each EESS has a suitable application range.

Contents

1. Introduction

Energy storage has long been recognized as a means of reducing petroleum demand and air pollution problems. Presently, the development of efficient and environmentally safe energy storage systems is an important and urgent issue to save our society from potentially serious damage due to various pollutants in the atmosphere. Demand for new energy storage systems is increasing for applications such as remote area power supply systems (like offshore platforms, telecommunication installations), stressed electricity supply systems, emergency back-up, as well as mobile applications. The supply of electric power to remote areas is becoming more attractive due to advancements in the photovoltaic (PV) technologies, concentrated solar thermal power systems (CSP) and wind power generation systems along with the development of advanced storage batteries. The wind power technology is commercially developed and efficient multi megawatt sized turbines are available. Moreover, the wind power is being utilized in many countries and today the total global wind power installed capacity surpassed 150 GW.

The use of batteries as portable electrical power source has increased and to some extent technology has not been able to

* Corresponding author at: P.O. Box 1634, KFUPM, Dhahran 31261, Saudi Arabia. Tel.: +966 3860 4432; fax: +966 3860 4509.
E-mail addresses: frahman@kfupm.edu.sa (F. Rahman), srehman@kfupm.edu.sa (S. Rehman), arif@kfupm.edu.sa (M.A. Abdul-Majeed).

1364-0321/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.rser.2011.07.153

keep pace with the demands. Longer lifetime and higher volumetric energy densities are needed for electric vehicles while electricity from renewable sources and load leveling applications are more sensitive to cost than to the gravimetric or volumetric energy densities. Computers, other electronic equipment and defense industries require higher reliability, safety and shelf life whereas the space stations are demanding enormous amounts of power storage capacity in a small volume and weight. The ideal high energy density battery has to meet many of the above demands and efforts are being made to cope with these stringent requirements. Throughout the world, therefore, enormous effort and funding is currently being diverted for the development of suitable battery systems for these applications. Lee and Gushee [1] stated that massive electricity storage is the critical technology needed by the renewable power if it is to become a major source of base load dispatchable power. They indicated that energy storage systems (EES) cost constitute about 30% of the total renewable power supply system cost. According to recent estimates electricity storage association (ESA) and KEMA, Inc. reported that more than 100,000 incremental jobs will be created by 2020 (a 10-year period) in energy storage sector, if investors received the proposed investment tax credit currently being debated in Congress based on Storage Act 2009 (S. 1091) [2].

This paper presents the climatic conditions and supply demand situation of power in Saudi Arabia. Subsequently, the assessment of different electric energy storage systems (EESS) for storing electricity generated from renewable energy sources was performed and suitable EESS based on various available technologies and economics has been identified.

2. Climatic conditions in Saudi Arabia

Usually batteries are used to store the energy produced by solar or wind to assure continuous supply 24/7. The batteries are very sensitive to weather conditions (temperature, relative humidity, barometric pressure, wind speed, etc.) and need to be evaluated both for efficiency and for working life degradation in the harsh environment of Saudi Arabia. Among all the weather parameters, temperature and relative humidity are very critical for battery efficiency and working life and hence should be considered while selecting a battery for energy storage purpose.

Saudi Arabia has a desert climate characterized by extreme heat during the day, an abrupt drop in temperature at night, and slight, erratic rainfall. Because of the influence of a subtropical high-pressure system and the many fluctuations in elevation, there is considerable variation in temperature and humidity. The two main extremes in climate are felt between the coastal lands and the interior.

Temperatures are different in each part of the country. Particularly in the central area and the north, the temperatures can be very high. From June through August, midday temperatures in the desert can soar to 50 °C (122 F) or more. The south has moderate temperatures, which can go as low as 10 °C (50 F) during the summer in the mountains of Sarawat in Asir. Along the coastal regions of the Red Sea and the Persian Gulf, the desert temperature is moderated by the proximity of these large bodies of water. Temperatures seldom rise above 38 °C, but the relative humidity is usually more than 85% and frequently 100% for extended periods. This combination produces a hot mist during the day and a warm fog at night. A uniform climate prevails in Najd, Al Qasim Province, and the great deserts. The average summer temperature is 45 °C, but readings of up to 54 °C are common. The heat becomes intense shortly after sunrise and lasts until sunset, followed by comparatively cool nights.

During the winter, the temperatures are moderate in general, but turning cold at night sometimes descending below freezing especially in mountainous areas of the west and along the northern border. Torrential rains fall along the Red Sea coast during March and April. In Najd, AL-Qasim Province, in the winter, the temperature seldom drops below 0 °C, but the almost total absence of humidity and the high wind-chill factor make a bitterly cold atmosphere. In the spring and autumn, temperatures average 29 °C.

The entire year's rainfall may consist of one or two torrential outbursts that flood the wadis and then rapidly disappear into the soil to be trapped above the layers of impervious rock. This is sufficient, however, to sustain forage growth. Although the average rainfall is 100 mm per year, whole regions may not experience rainfall for several years. When such droughts occur, as they did in the north in 1957 and 1958, affected areas may become incapable of sustaining either livestock or agriculture. The region of Asir is subject to Indian Ocean monsoons, usually occurring between October and March. An average of 300 mm of rainfall occurs during this period which is about 60% of the annual total. Additionally, in Asir and the southern Hijaz, condensation caused by the higher mountain slopes contributes to the total rainfall.

Prevailing winds are from the north, and, when they blow, coastal areas become bearable in the summer and even pleasant in winter. A southerly wind is accompanied invariably by an increase in temperature and humidity and by a particular kind of storm known in the gulf area as a kauf. In late spring and early summer, a strong northwesterly wind, the shamal, blows; it is particularly severe in eastern Arabia and continues for almost 3 months. The shamal produces sandstorms and dust storms that can decrease visibility to a few meters.

The mean maximum and minimum values of temperature over a period of 35 years, i.e. from 1970 to 2006 are summarized in Table 1. The long-term mean temperature was found to vary between a minimum of 18.6 °C at Abha and a maximum of 30.2 °C at Gizan. On the other hand the extreme maximum temperature varied between 34.1 °C and 51 °C corresponding to Abha and Qaisumah stations, respectively. So, any energy storage system being considered for Saudi Arabia should have a tolerance of withstanding a maximum temperature of about 50–55 °C and minimum temperature of −10 °C. The contour maps of mean, maximum and minimum temperatures; mean relative humidity; mean barometric pressure; mean and maximum wind speeds; and maximum rain fall over Saudi Arabia are shown in Figs. A.1–A.8, respectively.

3. Supply demand situation of power in Saudi Arabia

The electric energy in the Kingdom of Saudi Arabia is provided mainly by the Saudi Electricity Company (SEC), SEC is divided in four operating areas, namely the Eastern, Central, Western and Southern operating Areas. The residential and commercial loads represent more than 60% of the SEC total load. A large portion of the loads is mainly from air conditioner, therefore, reducing the use of energy at the peak hours and build at off-peak hours, look like a viable option.

To study the viability, the hourly load data for SEC four operating areas for the year 2006 were obtained. In this paper preliminary assessment is conducted for the Central Operating Area (COA). COA was chosen for the assessment as the load in COA is mostly residential and commercial and the difference between the daily peak and minimum load is quite large. The peak load recorded in the year 2006 was 9725 MW and occurred in the month of July, the total annual energy was 52,794 GWh. The minimum load recorded was 2133 MW and occurred in the month of January. The value of peak to minimum ratio for COA is 4.56 and the annual load factor is 0.62. Fig. 1 shows the peak day load for COA, the maximum load during the day was 9725 MW and it occurred at 1400 h on July 1, 2006. The minimum load for the day was 7290 MW and the average load for the day was 8169 MW. It can be seen from Fig. 1 that the load

Table 1
Long-term statistics of weather parameters for 20 meteorological stations.

S. No.	Station	Pressure (mb)	Rain (mm)	Temperature (°C)			Relative humidity (%)	Wind speed (m/s)	
		Mean	Max	Mean	Min	Max	Mean	Mean	Max
1.	Dhahran	1006.7	125.0	26.4	2.5	49.0	52.5	4.38	11.8
2.	Gizan	1007.7	90.0	30.2	11.8	45.3	68.4	3.24	7.7
3.	Guriat	954.8	36.5	19.5	−8.0	47.6	43.5	4.22	16.5
4.	Jeddah	1007.3	55.0	28.2	9.8	49.0	61.4	3.71	11.3
5.	Turaif	916.9	25.7	19.0	−8.0	45.5	40.3	4.33	14.4
6.	Riyadh	942.4	70.0	26.7	0.0	47.8	26.2	3.09	8.8
7.	Yanbu	1007.8	73.2	27.7	4.7	49.0	53.8	3.76	10.3
8.	Abha	794.0	119.9	18.6	0.0	34.1	54.6	2.94	14.9
9.	Hail	901.3	47.5	22.4	−9.4	44.5	33.2	3.24	10.8
10.	Al-Jouf	936.1	34.0	22.0	−6.0	46.7	32.1	4.02	15.9
11.	Al-Wejh	1007.9	116.0	25.1	5.1	46.0	64.6	4.43	11.8
12.	Arar	949.6	38.0	22.2	−5.6	48.2	36.2	3.61	12.9
13.	Bisha	884.0	40.0	25.9	0.3	44.8	29.3	2.47	10.3
14.	Gassim	937.6	86.0	25.1	−4.0	49.0	29.0	2.78	9.3
15.	Khamis	797.9	99.0	19.8	1.5	35.0	51.4	3.14	12.9
16.	Nejran	879.4	157.0	25.7	1.0	44.0	30.1	2.10	8.8
17.	Qaisumah	969.5	64.0	25.5	−4.0	51.0	31.4	3.55	11.8
18.	Rafha	960.3	121.0	23.4	−5.8	49.0	38.4	3.86	12.4
19.	Tabouk	926.0	36.0	22.1	−3.5	46.4	34.0	2.73	15.5
20.	Taif	855.4	169.0	23.1	−1.5	40.2	43.3	3.66	10.3

Mean: based on daily mean values during 1990–2006; Min: minimum, Based on daily minimum values during 1990–2006; Max: maximum, Based on daily maximum values during 1990–2006.

remains below 8500 MW for around 16 h and above the 8500 MW mark for around 8 h. If the load during the peak hours is supplied through any EESS system, the EESS system could be charged during the off peak hours.

4. Assessment of energy storage technologies

There is no single energy storage system that fits all the applications. Each application has to be studied and an appropriate ESS has to be selected depending upon the priority such as high energy density, reliability or low cost and is it for smaller or longer duration and so on. The main focus in this study is ESS related to utilization of power generated from renewable sources such as PV, CSP or wind also termed as energy management applications. The technical requirements for electrical energy storage systems for stationary applications are somewhat different than the requirements for vehicular storage. Automotive applications need small footprint and high power output. For utility applications cost is the most important factor and storage facilities need to be sized in the tens or hundreds of megawatts for duration of few hours. ESS have a number of application in the electrical power system, they are divide into three main categories:

Power quality: Stored energy, in these applications, *is only applied for seconds or less*, as needed, to assure continuity of quality power.

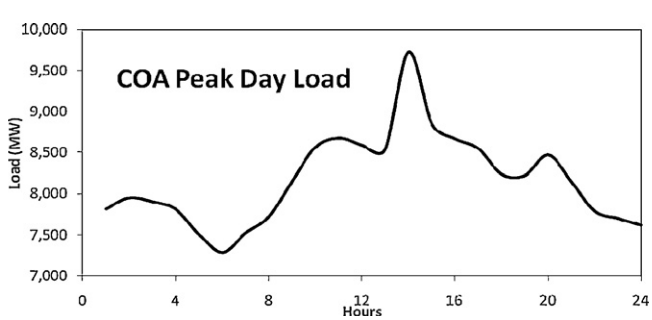


Fig. 1. Load variations during the peak load day in the central operational area (COA).

Bridging power: Stored energy, in these applications, is used for *seconds to minutes* to assure continuity of service when switching from one source of energy generation to another.

Energy management: Storage media, in these applications, is used to decouple the timing of generation and consumption of electric energy. A typical application is load leveling, which involves the charging of storage when energy cost is low and utilization as needed. This would also enable consumers to be grid-independent for *many hours*.

Fig. 2 illustrates various types of energy storage systems and their possible applications based on different requirements of the industry and community.

Materials research is contributing to the improvement of advanced batteries through work on nano-structured membranes, tailored electrolytes, and new electrodes. It is hoped that research will result in truly novel storage concepts in the near future and allow storage to be commonplace on the grid. The use of stored energy for the real time and short notice (milliseconds to a few minutes) support and optimization of the generation,

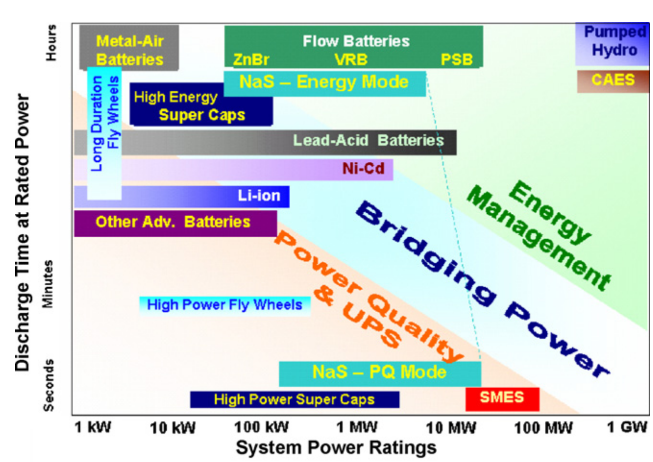


Fig. 2. Energy storage systems illustrating storage size and discharge time at rated power.
Source: ESA [11].

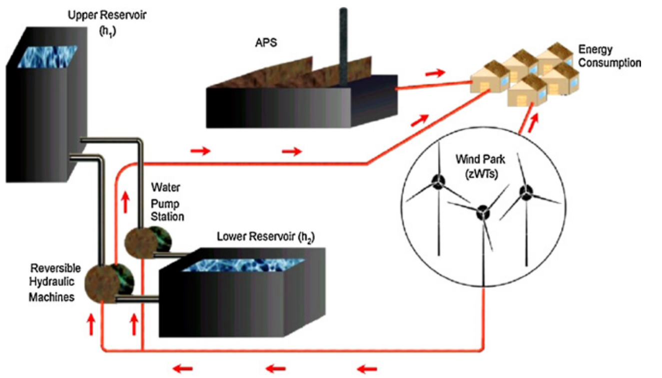


Fig. 3. Schematic of a conventional pumped-storage development [1].

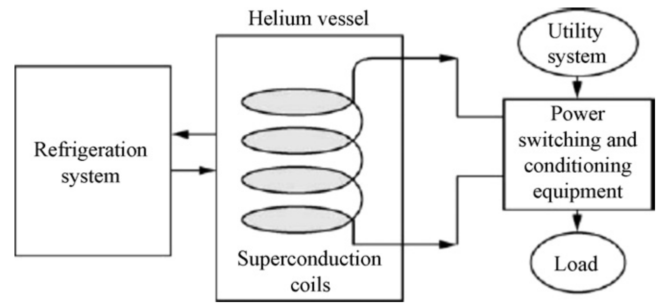


Fig. 4. Superconducting magnetic energy storage (SMES) system.

transmission and distribution (G, T&D) system has been limited to date to pumped hydro systems and, in a couple of instances, lead-acid or nickel cadmium batteries. Recent commercial advancements in energy storage and power electronic technologies are providing new opportunities to use energy storage in grid stabilization, grid operation support, distribution power quality, load shifting and intermittent renewable, e.g. wind generation, applications. The major energy storage systems are:

(1) Mechanical systems (pumped hydro, compressed air energy storage (CAES), flywheels),
(2) Electrical systems (capacitors and ultra capacitors, superconducting magnetic energy storage (SMES)),
(3) Chemical/electrochemical systems (metal-air, flow batteries, Li-ion battery, NaS battery, hydrogen energy storage).

5. Description of various energy storage systems

Electrical energy storage (EES) technologies are at various stages of development and deployment.

5.1. Mechanical systems

The mechanical storage system includes the pumped hydro systems (PHS), flywheels and compressed air energy storage (CAES). For example pumped hydro is the most widespread large-scale storage technology deployed on power systems; it is technically and commercially mature. Generally, the pumped hydroelectric storage system is used in power plants for load balancing or peak load shaving.

(1) In pumped hydroelectric energy storage systems, water is pumped to a higher elevation and then released and gravity-fed through a turbine that generates electricity. Conventional PHS uses two water reservoirs, separated vertically. During off peak hours water is pumped from the lower reservoir to the upper reservoir. When required, the water flow is reversed to generate electricity. Some high dam hydro plants have a storage capability and can be dispatched as a pumped hydro. Underground pumped storage, using flooded mine shafts or other cavities, are also technically possible. Open sea can also be used as the lower reservoir. A schematic view of a pumped hydroelectric storage system is shown in Fig. 3 [3].
(2) The second category of mechanical storage systems includes flywheels which have been around for thousands of years [4]. The earliest application is likely the potter's wheel. Perhaps the most common application in more recent times has been in internal combustion engines. Advances in power electronics, magnetic bearings, and flywheel materials coupled with innovative integration of components have resulted in direct current (DC) flywheel energy storage systems that can be used as a substitute or supplement to batteries in uninterruptible power supply (UPS) systems. In a flywheel energy storage system [5,6], kinetic energy is stored by causing a disk or rotor to spin on its axis. The amount of energy stored in a flywheel is directly proportional to the rotor's mass moment of inertia and the square of its rotational speed. When short-term back-up power is required the flywheel takes advantage of the rotor's inertia and the kinetic energy previously stored is converted into electricity. Most modern flywheel energy storage systems consist of a massive rotating cylinder that is substantially supported on a stator by magnetically levitated bearings that eliminate bearing wear and increase system life.
(3) The third category of mechanical energy storage includes the compressed air energy system (CAES). Off-peak (low-cost) electrical power is used to compress air into an underground air-storage "vessel" (the Norton mine), and later the air is used to feed a gas-fired turbine generator complex to generate electricity during on-peak (high-price) times. At utility scale, it can be stored during periods of low energy demand (off-peak), for use in meeting periods of higher demand (peak load).

5.2. Electrical systems

Superconducting magnetic energy storage (SMES) systems store energy in the magnetic field created by the flow of direct current in a superconducting coil which has been cryogenically cooled to a temperature below its superconducting critical temperature. It is the only known technology to store electrical energy directly into electric current [7]. It stores electric energy as direct current passing through an inductor (coil) made from a superconducting material and circular so that current circulate indefinitely with almost zero loss [8]. A typical SMES system includes three parts: superconducting coil, power conditioning system and cryogenically cooled refrigerator as shown in Fig. 4. To maintain the inductor in its superconducting state, it is immersed in liquid helium contained in a vacuum-insulated cryostat. Typically the conductor is made of niobium-titanium, and the coolant can be liquid helium at 4.2 K, or super fluid helium at 1.8 K. Once the superconducting coil is charged, the current will not decay and the magnetic energy can be stored indefinitely.

The stored energy can be released back to the network by discharging the coil. SMES loses the least amount of electricity in the energy storage process compared to other methods of storing energy. SMES systems are highly efficient; the round-trip efficiency is greater than 95% [9]. However, the major problem confronting the implementation of SMES units are the high cost and the environmental issues associated with strong magnetic fields. Due to the energy requirements of refrigeration and the high cost of superconducting wire, SMES is currently used for short duration energy

storage for large industrial customers. Therefore, SMES is most commonly devoted to improving power quality.

Electric double-layer capacitors, also known as supercapacitors, electrochemical double layer capacitors (EDLCs), or ultracapacitors, are electrochemical capacitors that have an unusually high energy density when compared to common capacitors, typically on the order of thousands of times greater than a high capacity electrolytic capacitor. In a conventional capacitor, energy is stored by the removal of charge carriers, typically electrons, from one metal plate and depositing them on another. This charge separation creates a potential between the two plates, which can be harnessed in an external circuit. In contrast with traditional capacitors, electric double-layer capacitors do not have a conventional dielectric. Rather than two separate plates separated by an intervening substance, these capacitors use "plates" that are in fact two layers of the same substrate, and their electrical properties, the so-called "electrical double layer", result in the effective separation of charge despite the vanishingly thin (on the order of nanometers) physical separation of the layers. The lack of need for a bulky layer of dielectric permits the packing of "plates" with much larger surface area into a given size, resulting in their extraordinarily high capacitances in practical sized packages. The supercapacitors applications are principally for high power or high energy dissipation for a short duration.

5.3. Chemical systems

The oldest and very established method of storing electricity is in the form of chemical energy in batteries. Battery systems range from mature, proven and reliable technologies (lead acid battery, invented in 1859) to new inventions which are at various levels of development such as NiCd, NaS, Li-ion and flow batteries. Among flow batteries VRB appears to be the more attractive based on technology and economics. Brief descriptions of few promising batteries are given below.

(1) *Lead acid battery* consists of a positive electrode made of lead dioxide and a negative lead electrode with a separator to electrically isolate the two positive and negative electrodes. Dilute sulfuric acid is the electrolyte which provides the sulfate ions for the discharge reactions. There are several types of lead acid batteries including the flooded battery that requires topping up with distilled water at regular intervals, the sealed maintenance free battery, which has a gelled or absorbed electrolyte, and the valve regulated lead acid battery. It is a popular storage device for power quality, UPS and other applications. However, it has low cycle life, cannot deep discharge and have problems of processing lead.

(2) *Nickel cadmium battery* comprises a nickel hydroxide positive electrode plate, a cadmium hydroxide negative electrode plate, a separator and an alkaline electrolyte. NiCd batteries are reliable, low maintenance and having relatively high energy density (50–75 Wh/kg) but low cycle life and high cost. It has environmental problem of disposing Cd being a toxic heavy metal.

(3) *Sodium sulfur battery* consists of liquid sulfur at the positive electrode and liquid sodium at the negative electrode as active materials separated by a solid beta alumina ceramic electrolyte. The electrolyte allows only the positive sodium ions to go through it and combine with the sulfur to form sodium polysulfides. During discharge, as positive Na^+ ions flow through the electrolyte and electrons flow in the external circuit of the battery producing about 2 V. This process is reversible as charging causes sodium polysulfides to release the positive sodium ions back through the electrolyte to recombine as elemental sodium. For good sodium ion conduction in this solid electrolyte, the operating temperature of the cell is maintained at 300–350 °C. To maintain high temperature, heat source is required, which uses battery's own stored energy, partially reducing the battery performance. This high temperature operation is advantageous for Saudi Arabian atmospheric conditions (high atmospheric temperatures around 55 °C). No self discharge occurs, and overall efficiency is as high as 90% including heat losses. Initial capital cost is high, but it is expected to fall as the manufacturing capacity expands.

(4) *Vanadium redox battery* consists of three major components: electrolytes, electrodes and membranes. The cell has two compartments (positive half cell and negative half cell) separated by a membrane, which prevents cross mixing of the electrolytes. Each side of the cell contains an inert electrode made of highly porous carbon felt. The electrolytes, both anolyte and catholyte, are stored in two large external reservoirs. The rechargeable electrolyte is circulated through the inert electrode where the electrochemical reactions occur. The electrolyte is one of the most important components, being not only the conductor of the ions, but also the energy storage medium. Hence, the volume of the electrolyte determines the capacity of the battery depending upon the vanadium concentration [10,12]. Schematic of the vanadium redox battery is shown in Fig. 5.

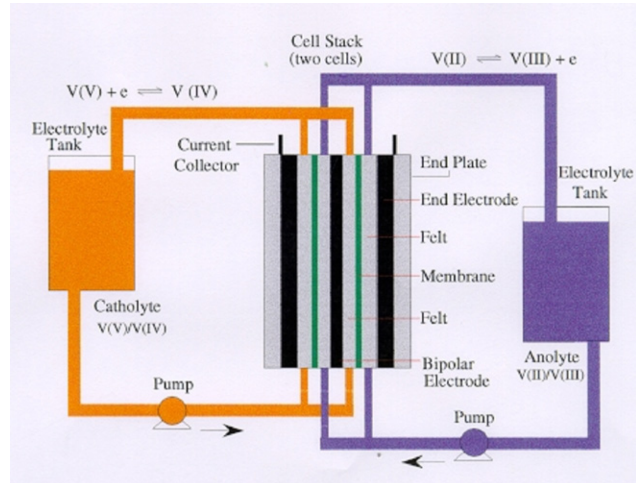


Fig. 5. Main features of vanadium redox battery [12].

The serious challenges the chemical storage technologies are facing are: cycle life, depth of discharge, reliability, efficiency and economics. For the storage of electricity generated by renewable sources there appears to be two low cost energy storage systems that are more suitable: vanadium redox battery and sodium sulfur battery.

6. Techno-economic evaluation of electricity storage systems

Table 2 presents the main features of selected EESS. For Saudi Arabia, the PHS and CAES that has special site requirements besides water and gas fuel is not a viable option and therefore eliminated from further discussion. SMES and supercapacitors are more suited for power quality applications for short duration and not for long duration needed in renewables. Li-ion batteries are expensive and needs special circuit for charging whereas renewables requires large scale low cost EESS.

The competing EESS technologies for stationary applications to utilize renewables are: lead-acid, flow batteries, NaS and NiCd. These EESS will be further assessed in terms of their properties.

Table 2
Advantages and disadvantages of major ESS [ESA, 11].

Technology	Advantages	Disadvantages	Commercial maturity	Application	Cost	Remarks
Mechanical energy storage						
Pumped storage hydro (PSH)	High capacity, Low efficiency	Special site requirement	High	Energy management	Low cost	Suitable for Load leveling
Compressed air energy storage (CAES)	High capacity	Special site requirement need gas fuel	High	Energy management	Low cost	Suitable for Load leveling
Flywheel	High power	Low energy density	High	Power quality management		Suitable for short duration in sec or min (voltage dip)
Electrical energy storage						
Capacitors/Supercapacitors	Long cycle life/high efficiency	Low energy density	Medium	Power quality management		Suitable for short duration in sec or min (voltage dip)
Superconducting magnetic energy storage (SMES)	High power	Low energy density and high production cost	Medium	Power quality management	High production cost	Suitable for short duration in sec or min (voltage dip)
Lead-acid		Limited cycle life when deeply discharged	High		Low capital cost	Renewables and power plants
Chemical energy storage						
Flow batteries: VRB, ZnBr, PSB	High capacity, independent power and energy ratings	Low energy density	Medium	Power quality and energy management		Renewables and power plants
NiCd	High power/high efficiency	High energy density, High Cost	High	Power quality and energy management		Renewables and power plants
Li-ion	High power/high efficiency	High cost and needs special charging circuit	Medium	Power quality management		Power quality management
Metal-air		Electrically not re-chargeable				
NaS			Medium	Power quality and energy management		Renewables and power plants

Table 3
Main features of competing EESS technologies [8].

Technology	VRB	PSB	ZnBr	NaS	NiCd	Lead acid
Efficiency (%)	85	75	75	89	60–65	65
Cycle life charge/discharge	13,000	NA	2500	3000	2500	1000
Size range (MW)	0.5–100	1–15	0.05–1	0.15–10	1–10	0.001–40
Operation temp. (°C)	0–40	50	50	350	Ambient	−5 to 40
Energy density (Wh/kg)	30	NA	50	150–240	50–75	50
Self discharge	Small	Small	Small	20% per day	0.6% per day	0.3% per day
Green	Yes		Yes	Yes	No	No
Disadvantages	Low energy density	Low cycle life	Low cycle life	High temp. system, complex safety design	Heavy metal Cd recycling issues	Issues with processing of lead. Limited cycle life when deeply discharged
Remarks	Most promising			2nd Best		

Table 3 presents major characteristics of the six EESS. Among the flow batteries, VRB appears to be better than PSB and ZnBr as they are of low capacities and low cycle life. Efficiency wise also VRB is slightly better. VRB is distinct from hybrid flow batteries (such as zinc-bromine and sodium-sulfur) which have one reactive electrode and therefore suffer from the degradation drawbacks of conventional batteries. Using only Vanadium in the electrolyte – as opposed to a blend of electrochemical elements – gives VRB systems the most competitive advantage in terms of operating cost, system life, maintenance, and safety. Size and weight of storage devices are important factors for certain applications but for large scale stationary applications such as renewables, it is not considered.

The efficiency and lifetime of selected energy storage systems is illustrated in Fig. 6. Efficiency and cycle life are two important parameters to consider along with other parameters before selecting a storage technology. Both of these parameters affect the overall storage cost. Low efficiency increases the effective energy cost as only a fraction of the stored energy could be utilized. Low cycle life also increases the total cost as the storage device needs to be replaced more often. The present values of these expenses need to be considered along with the capital cost and operating expenses to obtain a better picture of the total ownership cost for a storage technology.

The competing EESS technologies for stationary applications to utilize renewables based on technology evaluation appears to be Lead-acid, VRB, NaS and NiCd. The three batteries are basically advanced batteries and lead-acid battery is included in the analysis to compare with the currently used EESS. A preliminary economic evaluation was performed based on available cost data.

The capital costs for different EESS are shown in Fig. 7. The capital costs have been adjusted to exclude the cost of power conversion electronics. The cost per unit energy has also been divided by the storage efficiency to obtain the cost per output (useful) energy. Installation cost also varies with the type and size of the storage and with location. The information here should only be used as a guide not as detailed data. The costs of storage technologies are changing as they evolve. The cost data in Fig. 7 is based on approximate values in 2002 and the expected mature values in a few years.

While capital cost is an important economic parameter, it should be realized that the total ownership cost (including the impact of equipment life and O&M costs) is a much more meaningful index for a complete economic analysis. For example, while the capital cost of lead-acid batteries is relatively low, they may not necessarily be the least expensive option for energy management (load leveling) due to their relatively short life for this type of application and limited by depth of discharged (DoD). The capital cost of NiCd is higher than NaS and VRB and it has Cd disposal/recycling problem.

Capital cost per cycle is illustrated in Fig. 8 for the competing EESS technologies. Per-cycle cost can be the best way to evaluate the cost of storing energy in a frequent charge/discharge application, such as renewables and load leveling in power plants. Fig. 8 shows the capital component of this cost, taking into account the impact of cycle life and efficiency. For a more complete per-cycle cost, one needs to also consider O&M, disposal, replacement and other ownership expenses, which may not be known for the emerging technologies. It is clear from Fig. 8 that VRB is having lowest per

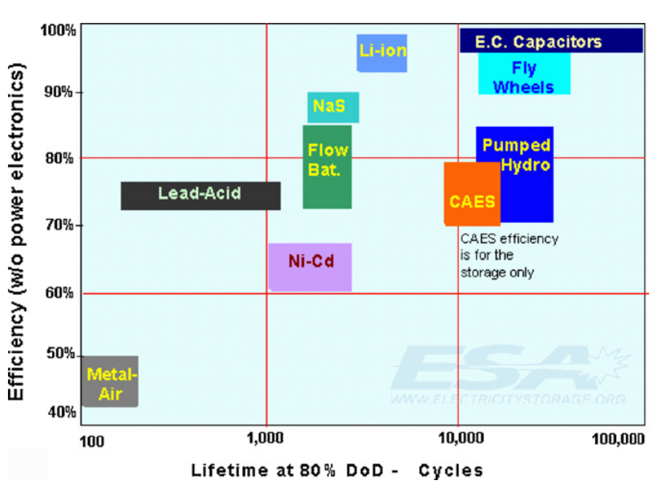


Fig. 6. Variation in efficiency with life time at 80% depth-of-discharge (DoD). Source: ESA [11].

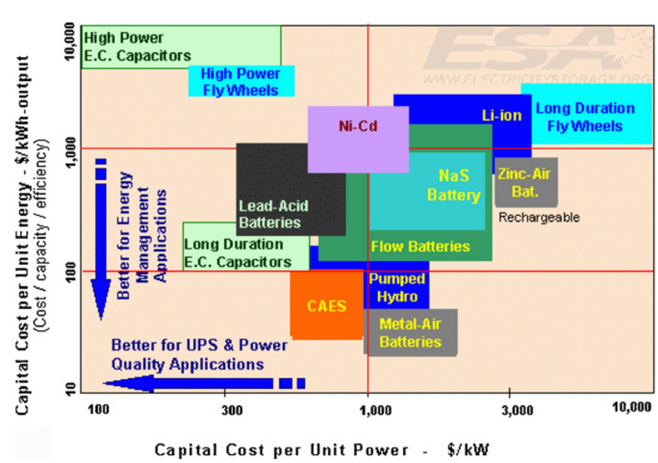


Fig. 7. Variation in capital cost per unit enrgy vs. cost per unit power. Source: ESA [11].

Table 4
Cost comparison of competing EESS [8,12].

Technology	VRB	NaS	NiCd	Lead acid	Reference
Power cost ($/KW)	600–1500	1000–3000	500–1500	300–600	Chen et al. [8]
Energy cost ($/KWh)	150–1000	300–500	800–1500	200–400	Chen et al. [8]
Cents/kWh-per cycle	5–80	8–20	20–100	20–100	Chen et al. [8]
O&M costs ($/KW h)	0.001	0.02		0.02	Huang et al. [13]
Overall assessment	Most promising	2nd best			

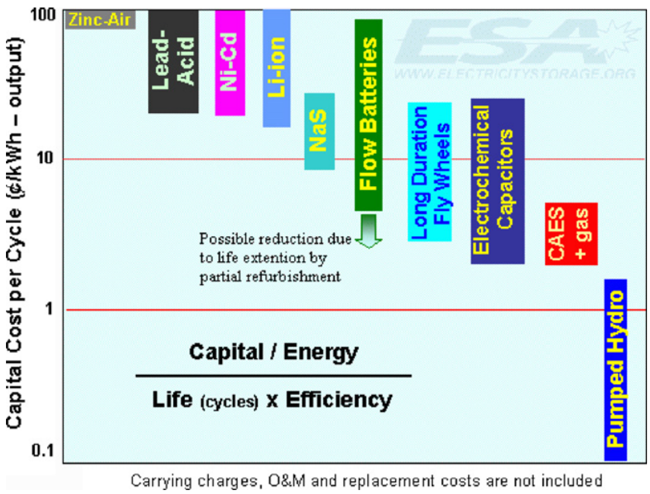


Fig. 8. Capital cost per cycle for selected EESS.
Source: ESA [11].

cycle cost followed by NaS, whereas per cycle cost for NiCd and lead-acid are relatively high. Since electrolyte of VRB has indefinite life and partial refurbishment can increase the battery life; the overall economics of VRB will be further improved when compared to NaS. Table 4 presents the cost data for the selected EESS technologies in terms of $/kW, $/kWh and cents/kWh per cycle and O&M cost. Based on data presented in Table 4 and Figs. 7 and 8, it can be concluded that VRB is a low cost battery among the four EESS technologies selected.

No single battery can meet all the requirements of ideal electrical energy storage system; however following observations is made based on above evaluation.

- Pumped storage, CAES, flow batteries, NaS, NiCd and lead acid batteries are suitable for renewable energy management.
- Pumped storage and CAES are low cost but generally utilized for huge capacities that are in GW and they require special site preparations.
- NiCd is a high energy density and high efficiency EES but its cost is high and it has problems with Cd disposal.
- Lead acid batteries are conventional batteries and are still being used in various EES systems commercially. It is reliable and low cost system. The major issues with lead acid batteries are: low cycle life with deep discharge, fast charging not possible, problems with mining and processing of lead.
- Redox flow batteries appear to be promising for renewable energy applications. In terms of efficiency, a simple electrolyte, full scalability and crossover resistance, the VRB is superior to PSB, Zn/Br and Fe/Cr flow batteries.

7. Conclusions

It can be concluded that for renewable energy applications, among the technologies reviewed here, vanadium redox and sodium-sulfur batteries seems promising. Flywheels have shown their applicability for frequency regulation. For serious power pumped hydro and compressed air are currently available.

Based on comprehensive technology assessment, economic evaluation and Saudi Arabian conditions, it is recommended to

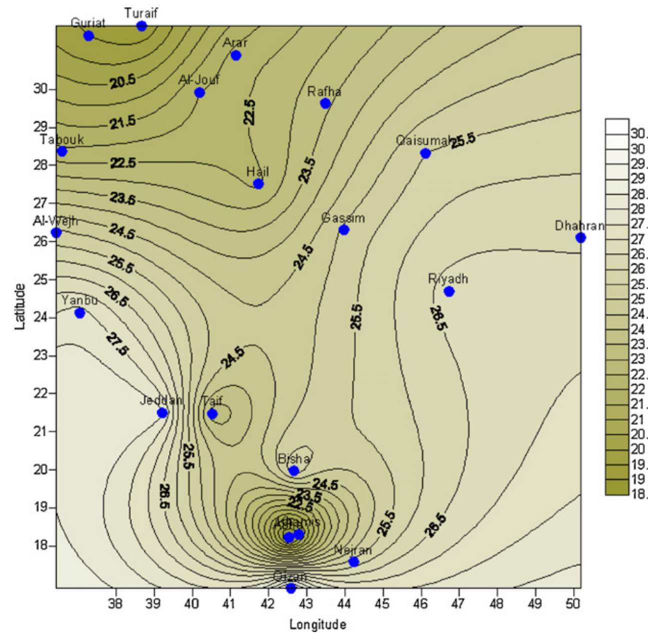


Fig. A.1. Variation of long-term mean temperature over Saudi Arabia.

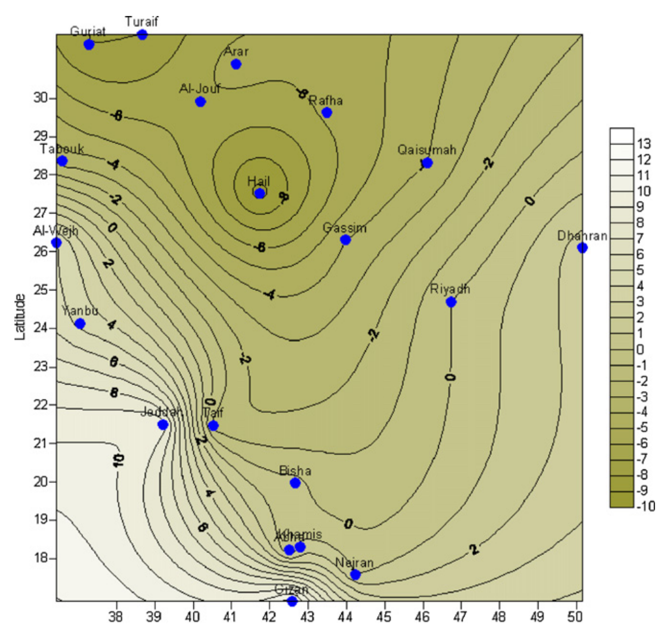


Fig. A.2. Variation of long-term minimum temperature over Saudi Arabia.

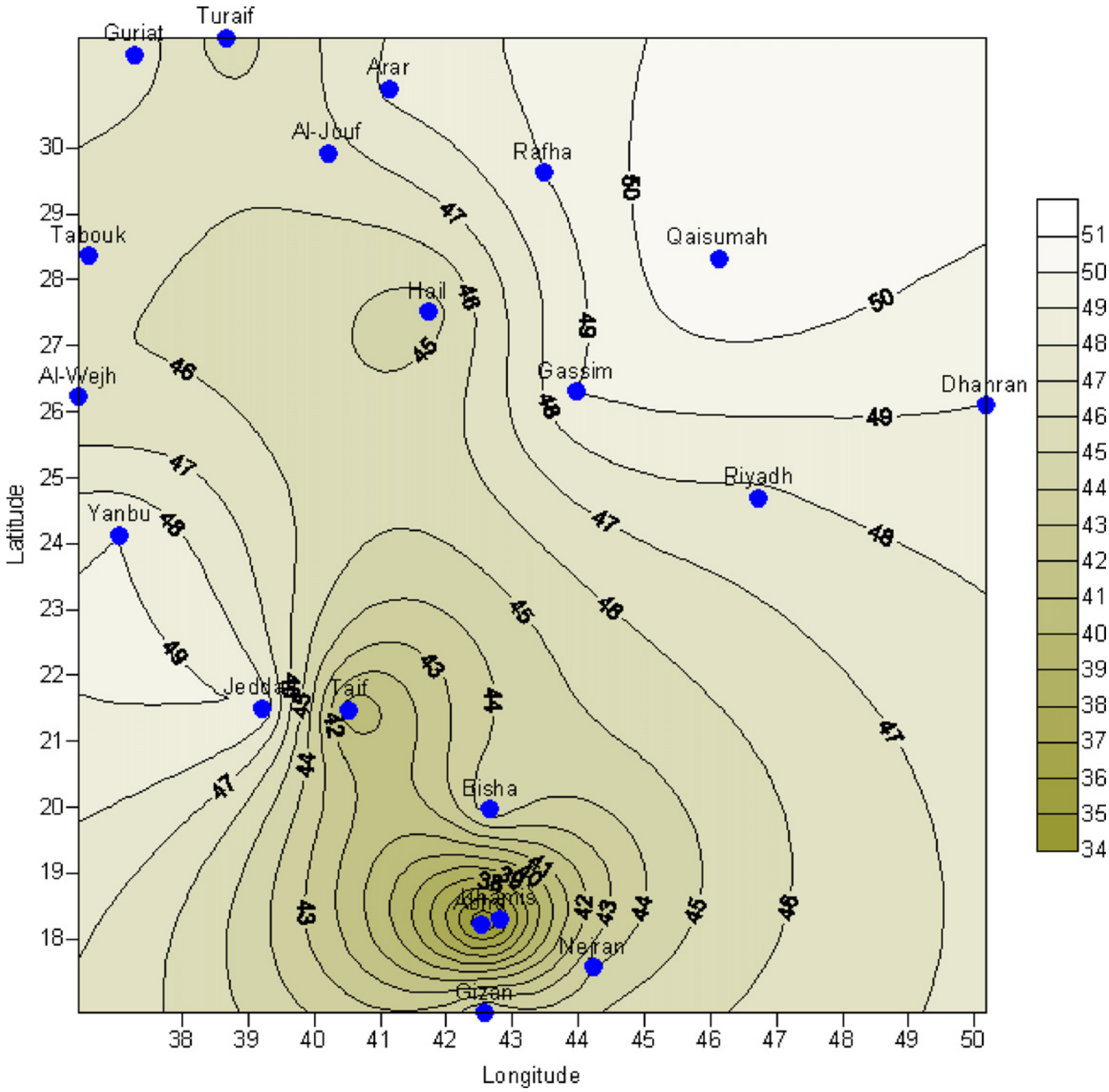


Fig. A.3. Variation of long-term maximum temperature over Saudi Arabia.

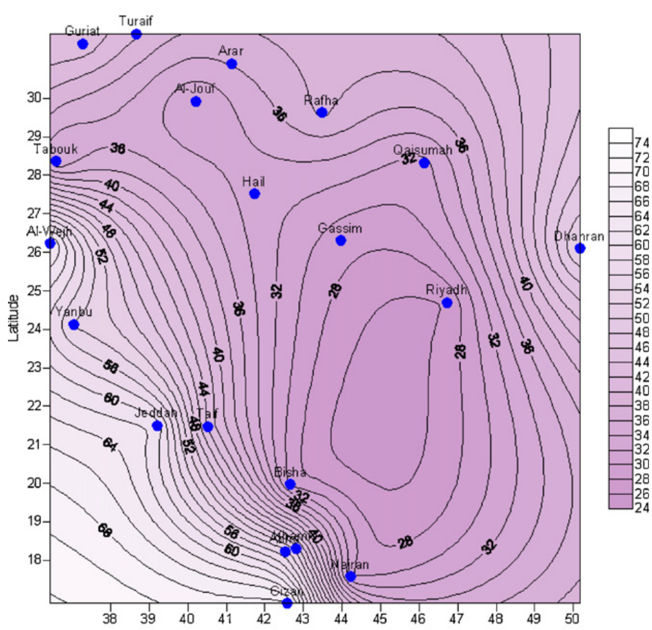


Fig. A.4. Variation of long-term mean relative humidity over Saudi Arabia.

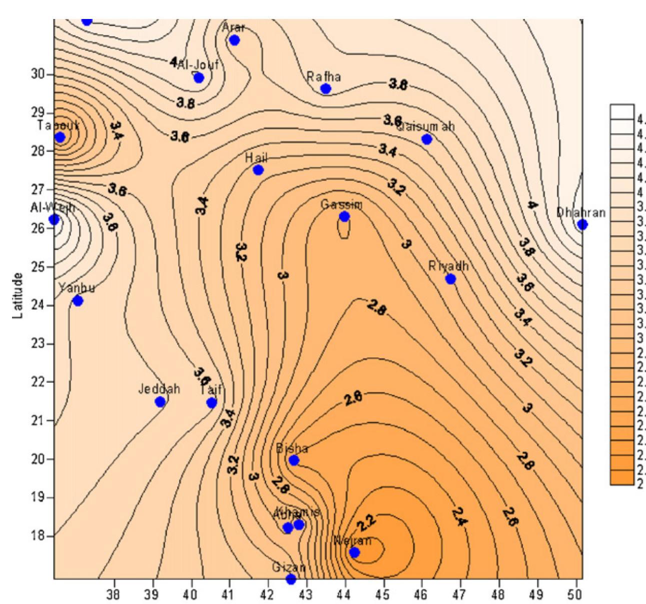


Fig. A.5. Variation of long-term mean wind speed pressure over Saudi Arabia.

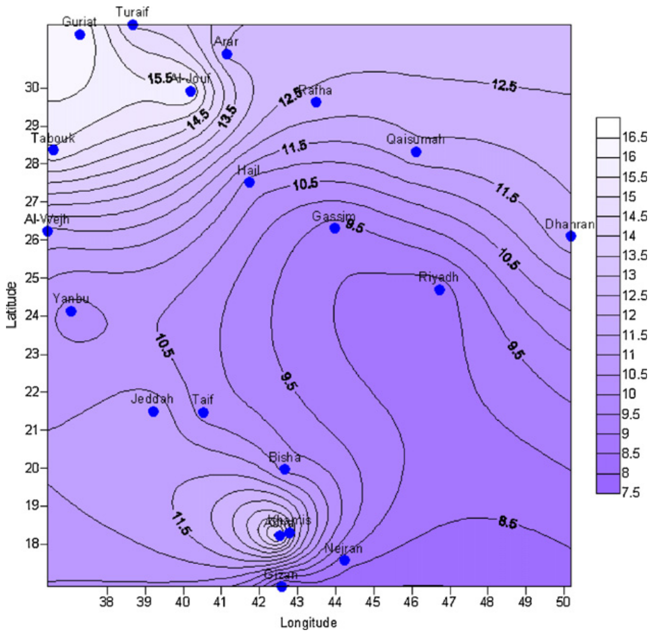


Fig. A.6. Variation of long-term maximum wind speed over Saudi Arabia.

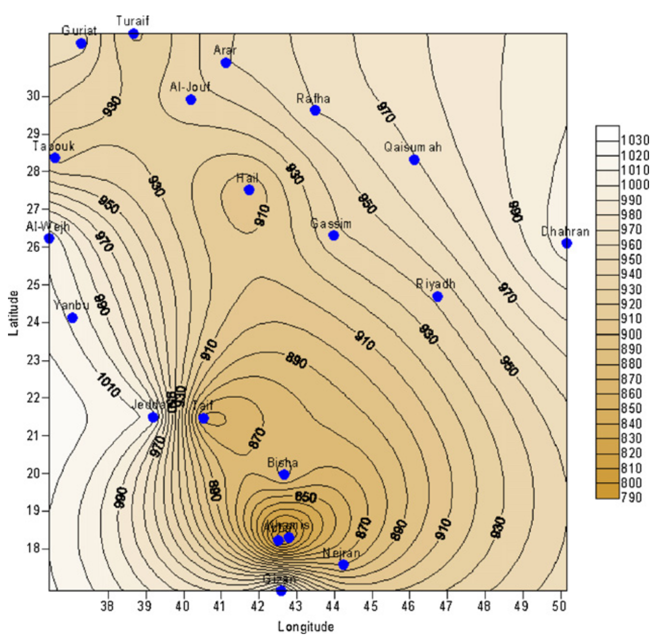


Fig. A.7. Variation of long-term barometric pressure over Saudi Arabia.

initiate R&D work to further improve on technology as well as economics. Two EESS that can be considered for further research are: VRB and NaS. These advanced energy storage system (VRB, NaS) can be integrated for storing electrical energy generated from renewable sources to improve dispatchability and reliability.

Finally it is worth mentioning that storage is the weakest link of the energy domain, but is a key element for the growth of renewable energies. There is an almost total absence of public awareness of the need for EESS. When the energy source is intermittent and

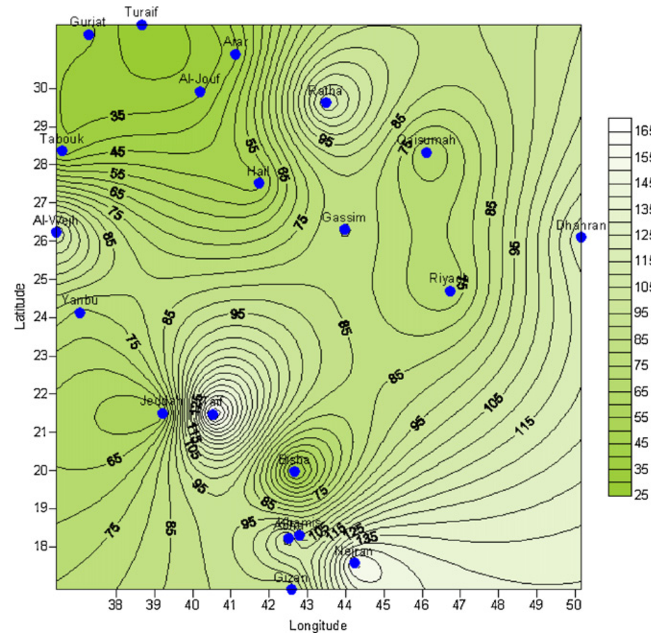


Fig. A.8. Variation of long-term maximum total rain fall in 1 day over Saudi Arabia.

fluctuating, EESS is the critical technology that will make it dispatchable in a reliable manner.

Acknowledgments

The authors are thankful to the Center of Research Excellence in Renewable Energy (CoRE-RE) at King Fahd University of Petroleum & Minerals, Dhahran established by Ministry of Higher Education, Saudi Arabia for providing the financial grant under Project No. CoRE-RE03.

Appendix A.

References

[1] Lee B, Gushee D. Massive electricity storage, An AIChE Paper; June 2008.
[2] KEMA, Inc. KEMA summary of ESA storage jobs report. Fairfax, VA: KEMA, Inc.; 2010, http://www.electricitystorage.org/images/uploads/docs/KEMA_-_ESA_Jobs_Report_Executive_Summary_FINAL_4-8-10.pdf.
[3] Kaldellis JK, Zafirakis D, Kavadias K. Techno-economic comparison of energy storage systems for island autonomous electrical networks. Renewable and Sustainable Energy Reviews 2009;13:378–92.
[4] DOE, US, Flywheel Energy Storage. An alternative to batteries for uninterruptible power supply systems. U.S. Department of Energy, Energy Efficiency and Renewable Energy, and the Authoring National Laboratory; 2009. Accessed on 28th April 2009, http://www.eere.energy.gov/femp/.
[5] Hull JR. Flywheels. Encyclopedia Energy 2004:695–704.
[6] Bolund B, Bernhoff H, Leijon M. Flywheel energy and power storage systems. Renewable and Sustainable Energy Reviews 2007;11:235–58.
[7] Cheung KYC, Cheung STH, Navin De Silvia RG, Juvonen MPT, Singh R, Woo JJ. Large-scale energy storage systems. Imperial College London, ISE2; 2002/2003.
[8] Chen H, Cong TN, Yang W, Tan C, Li Y, Ding Y. Progress in electrical energy storage system: a critical review. Progress in Natural Science 2009;19:291–312.
[9] Wikipedia, Superconducting Magnetic Energy Storage.
[10] Rahman F, Skyllas-Kazacos M. Optimization of supersaturated vanadium electrolyte for high energy density vanadium redox battery. In: 4th international conference and exhibition on chemistry in industry. 2000.
[11] Energy Storage Association (ESA); 2009.
[12] Rahman F, Skyllas-Kazacos M. Solubility of vanadyl sulfate in concentrated sulfuric acid solutions. Journal of Power Sources 1998;72:105–10.
[13] Huang KL, Li X, Liu S, Tan N, Chen L. Research progress of vanadium redox flow battery for energy storage in China. Renewable Energy 2008;33:186–92.